

SULFATE DEPOSITION IN REGOLITH EXPOSED IN TRENCHES ON THE PLAINS BETWEEN THE SPIRIT LANDING SITE AND COLUMBIA HILLS IN GUSEV CRATER, MARS, Alian Wang¹, L. A. Haskin¹, S. W. Squyres², R. Arvidson¹, L. Crumpler³, R. Gellert⁴, J. Hurowitz⁵, C. Schröder⁶, N. Tosca⁵, K. Herkenhoff⁷, B. L. Jolliff¹, and the Athena Science Team, ¹Dept. Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130; ²Dept. Astronomy, Cornell University, Ithaca, NY 14853, USA; ³New Mexico Museum of Natural History and Science, 1800 Mountain Road, NW, Albuquerque, NM 87104, USA; ⁴Max-Planck-Institut für Chemie, J. J. Becher-Weg 27, D55128 Mainz, Germany; ⁵Department of Geosciences, State University of New York, Stony Brook, NY 11794-2100, USA; ⁶Institut für Anorganische und Analytische Chemie, Johannes Gutenberg-Universität, Staudinger Weg 9, D-55128 Mainz, Germany; ⁷Astrogeology Team, USGS, Flagstaff, AZ 86001; (alianw@levee.wustl.edu).

Background: During its exploration within Gusev crater between sol 01 and sol 158, the Spirit rover dug three trenches (Fig. 1) to expose the subsurface regolith [1, 2, 9]. Laguna trench (~6 cm deep, ~203 m from the rim of Bonneville crater) was dug in Laguna Hollow at the boundary of the impact ejecta from Bonneville crater and the surrounding plains. The Big Hole trench (~6-7 cm deep) and The Boroughs trench (~11 cm deep) were dug in the plains between the Bonneville crater and the Columbia Hills (~556 m and ~1698 m from the rim of Bonneville crater respectively). The top, wall and floor regolith of the three trenches were investigated using the entire set of Athena scientific instruments [10].

Laguna Trench: Both the MiniTES and Mössbauer spectra indicate basaltic mineralogy at the top and within the trench [6,7], consistent with the compositional chemistry obtained by APXS [5]. Compositional data further show that the wall and floor regolith are indistinguishable from that of typical Gusev disturbed soils measured in rover wheel tracks (≤ 1 cm depth). Vis-NIR spectra obtained using the multi-filter Pancam images [3] indicate a very thin, highly oxidized layer (< 1 mm) of surface dust, an observation confirmed by $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ values from Mössbauer data (0.30 for surface and 0.22-0.23 for subsurface). The higher oxidation state of the surface dust corresponds to a high proportion of nanophase Fe-oxides. The microscopic images [4] show homogeneous, sand-sized grains in subsurface regolith. The data set overall suggests that Laguna Hollow was filled with basaltic sand brought in by aeolian process; the regolith exposed by the trench activity is relatively young.

Big Hole and The Boroughs Trenches: These two trenches were selected at topographically low plains, in areas with low

thermal inertia, away from fresh impact craters and from dust-filled hollows, purposely to seek mature regolith, which may hold a record of ancient aqueous interactions at Gusev.

Although both MiniTES and Mössbauer spectra suggest generally basaltic mineralogy for the subsurface regoliths within

these trenches, the mineral modes implied by Mössbauer data suggest a decrease of $\text{Fe}^{2+}_{\text{olivine}}$ and $\text{Fe}^{2+}_{\text{pyroxene/glass}}$, accompanied by an increase of $\text{Fe}^{3+}_{\text{npOx}}$, i.e., an overall higher oxidation state than the surface material, unlike Laguna trench. The highest $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ values among Gusev soils (0.43 - 0.44) occur in the floor regolith (~6-7 cm depth) of the Big Hole trench and in the wall regolith (~4 cm depth) of The Boroughs trench, with values for their surface materials in the 0.26-0.27 range, and 0.37 at The Boroughs floor (~11 cm depth).

The high oxidation state at depth within The Boroughs trench is accompanied by significant increases in the concentrations of S, Br, and Mg (only slight increase in Cl). A positive linear correlation between MgO and SO_3 and a negative linear correlation between Al_2O_3 and SO_3 (Fig. 2) indicate clearly the deposition of Mg-sulfates in the subsurface regolith, and the dilution of basaltic silicates by mixing with evaporite components. The multi-filter Pancam images

show light-toned materials being dug out from the trench [11], and the Pancam Vis-NIR spectra support a fairly high oxidation state of subsurface regolith. The microscopic images show poorly sorted sand, granules, pebbles, and cobbles within the trenches, indicating that the subsurface regolith is not a product of recent aeolian processes.

General mineralogy of the subsurface regolith at The Boroughs trench: In most Gusev soils (undisturbed and disturbed), the concentration ratios of S, Cl, and Mg are

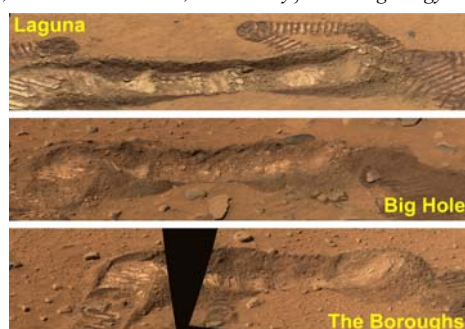


Fig. 1 Nearly true color Pancam images of three trenches

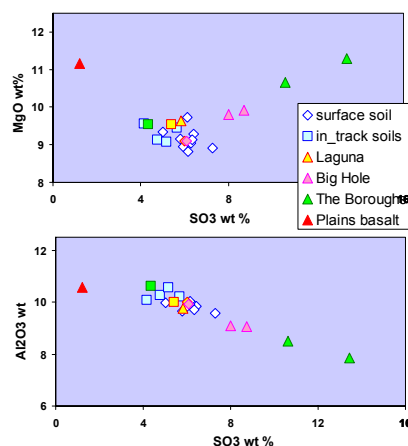


Fig. 2 Composition of trench regolith materials compared to Gusev surface regolith and an average Gusev Plains basalt composition (diamond=surface; square=shallow depth, triangle=deep depth)

roughly constant, but they differ significantly in The Boroughs trench and show extended concentration ranges. The wall regolith at The Boroughs has an Mg concentration ~25% higher than typical Gusev soils and even slightly higher than the average Gusev plains basaltic rocks [5, 8], which suggests lateral transportation and accumulation by processes involving either aqueous fluids or impacts.

Four types of analysis were used to estimate the general mineralogy of the subsurface regolith. To a first approximation, by subtracting a percentage of top regolith composition from that of the wall regolith (richest in S) towards zero concentration of Al_2O_3 , we found that the compositional remainder has $\text{MgO}+\text{CaO} \approx \text{SO}_3$ ($\text{MgO}/\text{CaO} \sim 7$) in molar %, along with extra SiO_2 and Fe_2O_3 . To further assess the mineralogy, we did a normative mineral modal analysis and a mass-balance mixing analysis based on APXS-derived elemental compositions, and using the results of Mössbauer analyses to constrain the Fe-oxides. We also used the APXS Fe concentration, Mössbauer derived $\text{Fe}^{2+}_{\text{olivine}}$ and Fo_{60} to calculate the mass% of olivine. From all three analyses, we obtained almost identical silicate mineral modes for the top regolith at The Boroughs trench. The MiniTES derived mineral abundance for olivine also agrees with our analyses, which indicate basaltic mineralogy (Fig. 3).

Comparing the wall regolith at The Boroughs trench with its top regolith, our analyses suggest no appreciable decreases in mass% Ca-feldspar and Ca-pyroxene, and ~10% decrease in olivine within the salt-free basaltic portion of the composition, indicating only minor alteration of the basaltic minerals. On the basis of this result, the composition of the top regolith can be used as a component in mass-balance mixing analysis of the wall regolith to determine what additional mineral phases might exist (Fig. 4): these appear to be sulfates (~16 wt%, ~13:2:1 for Mg- SO_4 , Ca- SO_4 and Fe- SO_4), silica (~5.4 wt%), and Fe-oxides (4.1 wt%). The H_2O of hydrated sulfates would account up to 4 wt% of wall regolith.

Discussions: Two hypotheses seem equally plausible for the formation of salty subsurface regolith at The Boroughs and Big Hole: (1) the multiple infiltration of brines accompanied by low degrees of alteration of local regolith components; and (2) the redistribution of more concentrated salty materials that formed at some distant location by impact.

The persistence of basaltic mineralogy with minor olivine alteration suggests a relatively low degree of

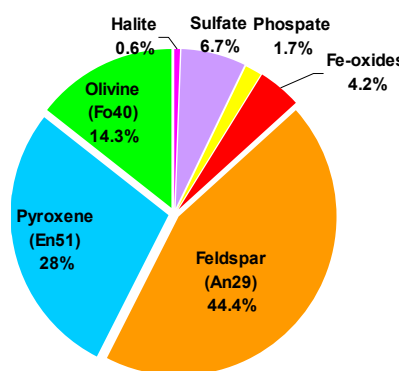


Fig. 3 Mineralogy of top regolith at The Boroughs.

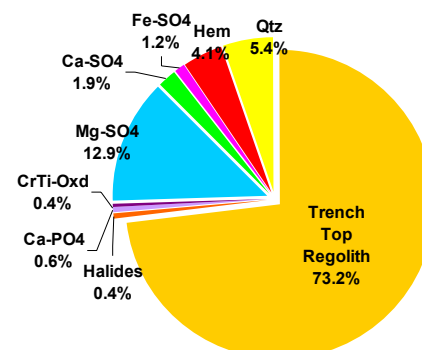


Fig. 4 Additional minerals in the wall regolith at The Boroughs

alteration of the rocks and regolith.

The fluid to rock ratios must have been low, thus only portions of olivine dissolved. Mg ions were released from olivine accompanied by the precipitation of silica and the conversion of $\text{Fe}^{2+}_{\text{olivine}}$ to Fe^{3+} -oxides. Mg ions were transported by the fluids with volatile elements and eventually deposited as Mg-sulfates in the regolith of topographically low plains. No appreciable alteration of clinopyroxene and plagioclase and the low ratio of Mg/Ca in sulfates suggest either that a low degree of alteration affected the general area at The Boroughs, or that a higher degree alteration occurred at some distance but Ca ions were deposited elsewhere.

The high concentrations and the variation of interelement ratios among S, Cl, and Br indicate that the compositions of the parent brines were not produced in a single, simple process. Multiple episodes of fluid to rock interactions, ion transportation, and repetitious precipitation and evaporation would be favorable. A lack of obvious crusty materials at the depth in the two trenches, however, argues against the *in situ* infiltration hypothesis.

Highly concentrated salts and strongly altered basaltic regolith (with high $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$) formed at some distant location(s) could be brought by impact ejecta, to be part of the mixture that is now The Boroughs subsurface regolith. In the highly altered basaltic materials, olivine might be totally consumed, and Ca-leaching from clinopyroxene and plagioclase might also have occurred. It is very possible that these two mechanisms both contributed to the formation of the observed subsurface regolith at the two trench sites.

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References: [1-8] S. W. Squyres et al.; R. E. Arvidson et al.; J. F. Bell III et al.; K. E. Herkenhoff et al.; R. Gellert et al.; R. V. Morris et al.; P. R. Christensen et al.; H. Y. McSweeney et al.; Science V305, p793-845, 2004. [9-11] S. W. Squyres et al.; L.A. Haskin et al.; A. Yen et al.; submitted to Nature.